Silicon Resonator Formed on LTCC Substrate with LSI Integration Compatibility for Application of Timing Device

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論 文 内 容 要 旨

Timing devices are considered as the heart of various electrical devices. They allow not only transmitting data but also synchronizing signals. Electrical resonators have been used for building timing device that can be easily integrated into a CMOS chip and have a very small size. However, it has a poor performance and a very small quality factor of about 10. For this reason, quartz crystal resonator which is one type of mechanical resonators with good performance, high stability, accurate frequency reference and high quality factor appeared. The two most disadvantages of the quartz crystal resonator are the large size and the difficult monolithic integration on a CMOS chip. Therefore, it is important to study novel resonators applicable to the timing device with the capability of further miniaturization. One of the promising options is a microfabricated resonator. It has a small size, high frequency range, high quality factor and LSI integration capabilities, yet it has low power consumption. Recently, two kinds of microresonators providing a wide range of operational frequencies, which are film bulk acoustic wave resonators (FBAR) and silicon capacitive resonators, have been developed.

FBAR, a high frequency piezoelectric micromechanical resonator, has similar structure to quartz structure that consists of piezoelectric material sandwiched between two metal electrodes. The piezoelectric materials, such as zinc oxide, aluminum nitride and PZT, have been widely studied. The motional resistance of FBAR structure is somewhat small. Film bulk acoustic wave resonators with a high quality factor Q are reported, but it is only about few thousand. Among the most promising option of the mechanical resonators is a silicon capacitive resonator that has the very high Q factor in mechanical resonator structures up to a few hundred thousand. The high Q factor characteristic is resulted in the resonator structure and its low internal friction. The electrodes of the silicon capacitive resonator are separated from the resonating body by air gap while the electrodes of piezoelectric mechanical resonator are directly contact with resonator which decreases the mechanical quality factor due to high internal loss of the electrode material. Therefore, the capacitive resonator can yield a much higher mechanical quality factor than that of piezoelectric mechanical resonators. Additionally, silicon is advantageous for resonator material in terms of low internal friction, applicability of well-developed microfabrication technology, and compatibility with integrated circuit technology. The resonant frequency of the capacitive resonator depends on the dimension of the structure; consequently, a wide range of resonant frequency can be obtained on the same chip.

However, there are still many challenges of silicon resonators for applications of timing devices. One of them is the large motional resistance, and hence, resulting high insertion loss that makes oscillation difficult. Resonant structures with a solid-filled gap are reported, where a high dielectric constant thin film (silicon nitride), which used to replace the air gap of conventional resonant structures on the dielectric film, is sandwiched between the electrode and the resonant body. The motional resistance of these structures shows a small value because of the high dielectric constant and very narrow solid gap. However, the resonator structure suffers from material mismatch between silicon and silicon nitride, which decreases the mechanical quality factor due to the high interface loss induced by the deposited silicon nitride film. Fabrication method of resonators with small capacitive gap using a thin oxide film as a sacrificial layer has been presented recently. However, this approach is slightly complex and high temperature process is required. Therefore, a method for attaining a low motional resistance would still be highly desirable. Another problem is the temperature drift and stability of the resonant frequency over a wide temperature range. Silicon resonator structures have a relatively large frequency drift over temperature in comparison to quartz resonators. Some compensation temperature techniques have been reported for the silicon resonator. Si-SiO_2 composite resonator was fabricated and encapsulated in a hermetic environment for double ended tuning fork structure. Temperature compensation of silicon resonators has achieved using degenerate boron-doping and boron-assisted aluminum doping, and silicon bulk acoustic reference oscillators with electrical temperature compensation has been reported.

There were many studies conducted on silicon resonators up to now. However, most of them have not been packaged yet to avoid viscous damping for obtaining a high quality factor and high stability of the resonance. Additionally, the packaging also helps to protect the device from the external environment and to avoid issues with moisture and particles for long-term operation. Packaging process for encapsulating and electrical interconnections is critical technology for practical applications of microdevices. One of the packaging methods is encapsulation using a thin-film package. However, this method requires high temperature process for the deposition of a thin film and outgassing. Thin-film packaging process based on a metal-organic thin-film is available at low temperature (<110^0C), but it also suffer from process incompatibilities. Getters can be used for vacuum packaging to absorb the desorbed gases, but it is difficult to integrate into thin-film package because they need to be deposited on the package ceiling. Packaging process using a conventional borosilicate glass substrate with electrical feed-through is reported. The problem of this method is the quality of via-holes with metal. The process for packaging using low temperature co-fired ceramic (LTCC) with the Au metal feed-through offers great potential to reduce cost and improve reliability.

This research aims at developing the integration technology of the resonator on LSI for applications of a timing device. This work brings out a new approach to combine a vacuum packaging technique with a silicon resonator on an LTCC substrate based on anodic bonding. Additionally, the models of a silicon micromechanical resonator with a high *Q* factor and small motional resistance are proposed, fabricated and evaluated.

A new approach to combine a vacuum packaging technique with a silicon resonator on an LTCC substrate with Au metal feed-through based on the anodic bonding technique is demonstrated. The proposal device can replace quartz crystal resonators and operate at the high frequency range. This device can simplify the integration of LSI for the application of timing device using a solder bonding technique. Silicon resonators are hermetically packaged on the basis of the anodic bonding technique. Firstly, the structures of the resonator are transferred onto the LTCC substrate using the anodic bonding of silicon and LTCC for electrical interconnections. Then, the resonator structures are packaged hermetically by the second anodic bonding of silicon and Tempax glass for encapsulation. The measured resonant frequency of the packaged device is 20.24 MHz and the high *Q* factor of 50,600 is observed without any kind of amplification.

The ultra high *Q* factor and low motional resistance have been demonstrated by a long bar type silicon resonator. The theoretical analysis and the experimental results show that the long bar type resonator body has higher *Q* factor and lower motional resistance that those of shorter resonator body. Additionally, the device is hermetically packaged using an LTCC substrate based on anodic bonding technique. The resonant characteristics before and after packaging process are evaluated. The resonator is excited in the extensional mode at a resonant frequency of 9.69 MHz. The value of *Q* factor measured for this device is 368,000 at vacuum chamber pressure of 0.01 Pa and 341,000 after packaging process.

The capacitive silicon resonator with movable electrode structures can reduce the motional resistance for lower insertion loss and also increase the tuning frequency range for compensation of the temperature drifts of the silicon resonators. Frequency characteristics of the silicon resonator of resonant frequency 9.65 MHz with a length of 500 μm, width of 440 μm and thickness of 5 μm were evaluated, and a high *Q* factor of 49,000 is achieved at a polarization voltage of 25 V. The measurement results have shown that the motional resistance is reduced by 200 times, the output signal (insertion loss) is increased by 21 dB and the tuning characteristic of the frequency is also increased by 7 times than that without movable electrode structures.

A fabrication method of silicon resonators using neutral beam etching technology is proposed to obtain narrow capacitive gap for small motional resistance. Frequency characteristics of the devices fabricated by NBE with the resonant frequency of 9.66 MHz with a length of 500 μm, width of 440 μm, and thickness of 5 μm are evaluated, and a high average *Q* factor value of around 78,000 is achieved. Additionally, the devices fabricated by both DRIE and NBE are evaluated and compared with each others. The devices fabricated by NBE show that the motional resistances are reduced by almost 11 times and their output signals are increased by approximately 15 dB than those fabricated by DRIE. Especially, devices fabricated by NBE provide the higher *Q* factors (from 75,000 to 82,000) than those (from 57,000 to 66,000) of devices fabricated by DRIE in the comparison of the same resonator parameters and measurement conditions. The resonator fabricated by NBE realizes a higher *Q* factor, lower insertion loss and smaller motional resistance than those obtained by DRIE. A new approach to fabricate silicon micromechanical resonator using NBE is proposed.

論文審査結果の要旨

マイクロ・ナノ加工技術を利用すると電気機械要素を小型，集積化することができ，近年，小型化されたセンサやデバイスが携帯機器などに利用されている。水晶発振子を用いたタイミングデバイスは，クロック信号を発生する素子であるが，小型化や，LSI の集積化が困難である欠点を有する。一方，シリコン振動子を用いたタイミングデバイスは小型化が可能であるため，近年，活発に研究が進められている。本論文では，タイミングデバイスに応用する目的で，容量型シリコン振動子を設計，製作，評価している。振動子は，3 次元配線を形成した低温同時焼成セラミックス(LTCC)基板を利用して真空パッケージングしている。本論文は，これらの研究成果をまとめたものであり，全編 8 章からなる。

第 1 章は緒言であり，本研究の背景や目的について述べている。

第 2 章では，LSI が集積化でき，バルク音響波振動モードを有する容量型シリコン振動子の構造，およびその動作原理や設計論について述べている。これは小型のタイミングデバイスを実現するための重要な成果である。

第 3 章では，シリコン振動子の作製方法について述べている。3 次元の貫通金属配線を有する LTCC 基板上にシリコンの振動子構造を陽極接合で転写し，さらに陽極接合でガラスの蓋をして真空封止するプロセスを開発している。これは，LSI が集積化可能な小型で高性能の発振子を実現するための重要な成果である。

第 4 章では，作製したシリコン振動子の評価結果について述べている。約 20MHz の共振周波数をもつ振動子を真空封止することで，50,600 の高い Q 値が得られている。これは，パッケージング技術によって作製された振動子が良好な振動特性を持つことを示したもので，重要な成果である。

第 5 章は，振動子のサイズ依存について調べたものである。振動子を長くすることで，等価直列抵抗が小さくなり，また Q 値が高くなることが述べられている。また，真空封止した振動子において，341,000 の高い Q 値が得られている。これは，ノイズが小さな発振子を実現するために重要な知見である。

第 6 章は，より小さな等価直列抵抗を得るために，駆動する電極を組み込んだ振動子について述べたものである。等価直列抵抗を小さくするには振動体と電極間のギャップを小さくする必要があり，これを静電力で駆動する電極を内蔵させて実現している。これは，実用化に向けた重要な成果である。

第 7 章では，中性粒子ビームエッチングの振動子作製への応用について述べている。中性粒子ビームエッチングを用いることで，電極と振動子間により狭いギャップが形成でき，等価直列抵抗が低減できる。また，さらに加工損失を減らし高い Q 値が得られることについて述べている。これは，加工損傷と電気機械特性に関連があることを示す重要な知見であり，中性粒子ビームエッチングが振動子の作製に有効であることを示す重要な成果である。

第 8 章は結論である。

以上要するに本論文は，タイミングデバイスへの応用を目的とし，LSI の集積化と整合性を持ち，LTCC 基板を用いて真空封止できるシリコンの振動子を開発して重要な成果を得たものであり，機械システムデザイン工学および微小機械構成学の発展に寄与することが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。